Frequency response analysis of the fiber optic hydrophone optimized for large diameter core fibers

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This paper demonstrates the procedure for designing, frequency response testing and optimization of a robust fiber optic hydrophone. Sensing head construction allows different fiber layouts, variable membrane to fiber distance and easy membrane change. Testing frequency response in various environmental conditions allows differentiating resonant peak originating from the membrane from range of peaks originating from sound source and resonator. Maximum sensitivity of the sensor response is achieved by optimizing the fiber-membrane distance while attaining sufficient light coupling and minimal mirror mass. Modular construction of the sensing head allows fast reconfiguration of the hydrophone for many types of liquids.

1. Introduction

Hydrophones can be used for measurements of pressure, density and salinity of liquids, acoustic field calibrations, and for numerous measurements in different industries. Fiber optic hydrophones have several advantages over conventional hydrophones such as high sensitivity, large dynamic range, multiplexing convenience, flexibility of design, immunity to electromagnetic interference and resistance to corrosive environment [1]. The potential for down-hole exploration of nature oil resources, seismic sensing arrays and subsea acoustic measurements is another advantage.

Although fiber optic hydrophones based on various principles have been demonstrated [2,3,4], most common principles are phase (interferometric sensors) and light intensity modulation. Interferometric hydrophones require a reference arm for comparing phase shift. The reference arm is a potential noise source and environmentally sensitive. Temperature differences between the sensing and reference arm can produce undesirable errors [5]. Sensor structure and signal processing of the phase modulation hydrophones is complex making them expensive. Sensor structures of the light intensity modulated hydrophones is generally simple and compact and therefore less expensive.

In this paper a fiber optic hydrophone based on light intensity modulation is presented. Simple in construction with easily interchangeable membrane and adjustable fiber position, this hydrophone can be swiftly modified for different fluids. In order to make the hydrophone as user friendly as possible we present a procedure for frequency response measurement capable of distinguishing the origin of resonant peaks. Using this procedure the hydrophone bandwidth can be designed experimentally without knowing acoustics source resonant peaks.

2. Sensing head construction

The sensing head of the proposed fiber optic hydrophone is a compact structure, yet it offers the possibility of part interchangeability. Sensing head is shown in Fig. 1. The head is composed of the main body, hollowed out to guide the input and output fibers, a closing bottom membrane and a top lid, all made from durable and floatable plastic. The hydrophone diameter is 50 mm and length is 70 mm. The top lid and the main body guide input and output fibers while at the other end the bottom lid holds the membrane. Thin, light and watertight membrane was made of silicone rubber. Screwing on the bottom lid provides variable tightening of the membrane which results in its different elasticity. A reflective mirror, 4 mm in diameter, made from thin paper film coated with silver layer was glued to the inner membrane surface. The air inside the watertight chamber is at the atmospheric pressure permitting the outside water to imposes some tension on the submerged membrane. Intensity modulation of the carrier light occurs when acoustic waves incident on the outer membrane surface cause displacement of the membrane and the mirror from stationary position.
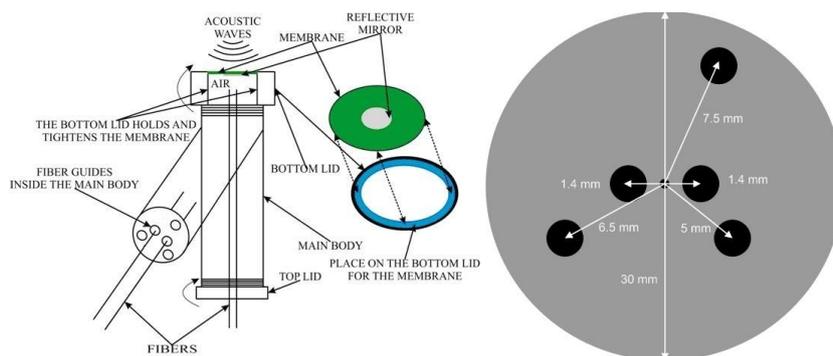
Fig. 1. Sensing head construction.

The sensing head is constructed to allow continuous change of fibers to membrane distance from 0 to 12 mm. Additionally there are five fiber guides inside the main body allowing nine different fiber configurations to be tested. Fiber position can be optimised for maximal sensitivity (e.g. as proposed by Li[6]) or for maximal received optical power, depending on the more critical requirement. Ability to change the sensing membrane and to adjust the optimal fiber position in two axes provides a method for adapting the hydrophone response to different fluids and applications. Large-core (1 mm) plastic step-index fibers with high numerical apertures have been used because they are robust and capture a significant amount of light.

Transimpedance resistance of 100 kΩ was used, with 150 pF capacitor in parallel, to limit bandwidth to 10 kHz and to improve stability. Gain was provided by NE5532, dual, low-noise, audio-operational amplifier, having a GBW (gain bandwidth product) of 10 MHz, input voltage noise specified at 5 nV/√Hz, and input current noise at 1 nA/√Hz. Photodiode input capacitance was 25 pF, with an additional 5 pF from circuit traces and operational amplifier input. Total noise at the output of the transimpedance stage can be calculated as 41 µV rms. If the SNR requirement is to be met, a minimum of 4 mV of rms signal is needed and this translates to 40 nA of photodiode current. Typical Si photodiode conversion efficiency at the used wavelength is 0.4 A/W meaning that a minimum light intensity of 100 nW is required to be present at the receiving fiber for a SNR of 1:100.

3. Experimental setup

The setup consists of a water tank, an optical source, the sensing head, fibers, optical receiver system, test acoustic wave sources and a tone generator, Fig. 2.
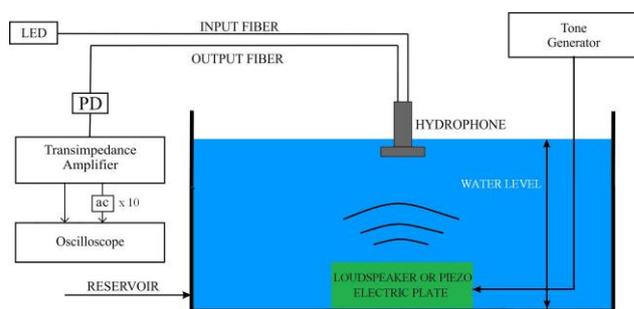

Fig. 2. Experimental setup.

For the light source we used a 625 nm red LED with maximal optical power of 50 mW. The light from the source travels by fiber to the sensing head, where it gets modulated by the reflective membrane that responds to incident acoustic wave, and is then guided by output fiber to the optical receiver. A photodiode in the transimpedance amplifier is used to receive the light from the output fiber and to convert the light into an electric signal which is then amplified. Output of this amplifier is DC coupled to the oscilloscope and also AC coupled (high pass filtered above 10 Hz) and further amplified by gain of 10 V/V and used to obtain measurement results.

The membrane response can be modeled as a second order system. To design the hydrophone bandwidth, resonance frequency and Q factor data are needed. These depend on membrane mass and elasticity as well as the fluid type. One can promptly obtain these data experimentally if one is able to distinguish the peak originating from the membrane from range of peaks originating from environment and source [7]. To single out the membrane peak, for frequency response measurements two different acoustic sources and two water levels are used. Two water levels in the reservoir provide two different resonant structures that generate different resonant peaks for equal excitation. A loudspeaker (10W power) and a piezoelectric plate (10W power) are used as different excitation sources giving raise to different response peaks for the same resonant structure. Only the peak common to different sources and resonators can be caused by the membrane.

Frequency and amplitude of the acoustic wave sources are adjusted with the tone generator. Excitation was sinusoidal with frequencies from 90 Hz to 4 kHz.

4. Results

We have tested two membranes, first of 1.8 g mass (which we will designate as heavy) and second of 1.75 g mass (which we will designate as light). Fig. 3 presents scan of the entire frequency range for light membrane. It should be noted that watertightning circle is an integral part of the membrane, but it is not moving, so the effective mass of the membrane is considerably smaller. From the array of peaks one singles out a membrane resonant peak present at 875 Hz common for both acoustic sources and water levels. Zoomed frequency scale at Fig. 4 clearly demonstrates matching of the peaks. Numerical comparison of peak matching is presented in Table 1. Other peaks are matched either for equal water level or same acoustic source.
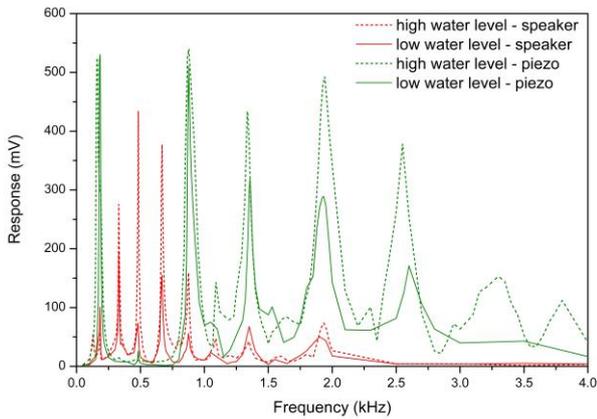
Table 1. Light Membrane peaks.

Peak No	Low water level piezo [Hz]	High water level piezo [Hz]	Low water level speaker [Hz]	High water level speaker [Hz]
1	160	180	185	185
2	330	350	330	330
3	500	482	483	480
4	700	650	669	668
5	**877**	**876**	**874**	**874**
6	1090	1050	1090	1050
7	1338	1356	1350	1350
8	1942	1932	1933	1900

Comparison of results for heavy and light membranes is presented in Fig. 5. Resonant peak belonging to the light membrane is up shifted compared to the resonant peak of the heavy membrane (315 Hz) because of its higher elasticity and lower mass, widening the bandwidth.

Fig. 3. Light membrane frequency response for different water levels and both acoustic sources.

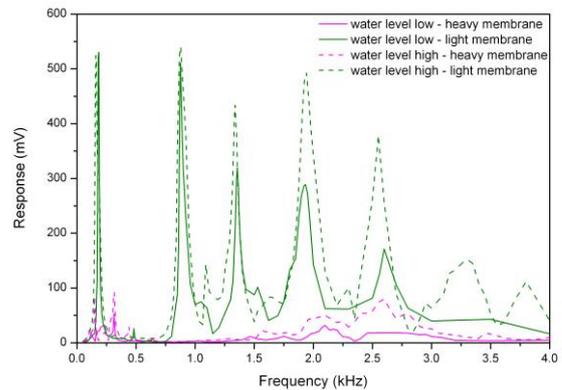*Fig. 5. Comparison of frequency responses of light and heavy membranes.*

To further increase the resonant frequency of the hydrophone one needs to further reduce the mass of the membrane and increase its elasticity. The mirror in our experiments is 4 mm in diameter. Further reduction of the mirror size would cause loss of detected optical power at the receiver if the distance between membrane and the fiber was optimized for highest sensitivity. This procedure is suitable for any liquid and provides a fast method for determining the appropriate membrane.

5. Conclusion

Robust and floating hydrophone sensing head with large core diameter fibers has been designed and tested. Sensing head was designed to allow optimization of the fiber position and distance to the membrane to obtain maximum sensitivity or maximal received optical power. Measurement setup was devised to differentiate peaks

Fig. 4. Zoom of the light membrane frequency response around the matching peak.

originating from sources and environment and that of the membrane. There is a single matching resonant peak visible for both water levels and different sound sources which originate from the hydrophone membrane. To up shift the position of the resonant peak we have increased membrane elasticity and reduced its mass. In addition, reflecting mirror size and mass have been minimized for the given fiber-membrane distance to increase the bandwidth of the frequency response. Modular construction of the sensing head coupled with proposed simple testing procedure allows fast reconfiguration of the hydrophone for many types of liquids.

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